A COMPARISON OF ENVIRONMENTAL DATA RECORDED BY ON-SITE HEAT STRESS MONITORS TO METEOROLOGICAL STATION DATA PROVIDED BY THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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ABSTRACT

Proper evaluation of the thermal environment is necessary for determining appropriate parameters for safe athletic participation with reduced risk of heat stress. The presence of microclimates has been shown to affect the ability to generalize activity modification recommendations across locations near each other. This study evaluated the differences in heat index (HI) and wet bulb globe temperature index (WBGT) between on-site measurements at secondary schools in Hawai`i and data collected by the closest National Oceanic and Atmospheric Administration (NOAA) meteorological station to each school. Flag categories based on NOAA HI and WBGT were underestimated more than 60% of days analyzed compared to on-site data. Majority of schools were recommended to use on-site data based on significant differences. The presence of microclimates in Hawai`i affect the ability to utilize NOAA data for determining activity modifications for reducing risk of heat stress, therefore on-site HI and WBGT are most appropriate and recommended.

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LIST OF ABBREVIATIONS/SYMBOLS

National Oceanic and Atmospheric Administration's National Weather Service……NWS

National Oceanic and Atmospheric Administration's National Climatic Data Center…..….NCDC

Wet bulb globe temperature index…….WBGT

Heat index……..HI

Dry bulb temperature……T_{db}

Wet bulb temperature……...T_{wb}

Globe bulb temperature……T_{gt}

Relative humidity……..…RH

Athletic trainer……..…AT

INTRODUCTION

The human body expends metabolic heat into the environment by radiation and air conduction, but as work or environmental heat increases, the body relies on the evaporative effect of sweating to cool.[1-3] The main environmental factors that affect heat stress are air temperature, relative humidity (RH), wind speed and solar radiation.[3] Increased air temperatures hinder the body's ability to lose heat by radiation.[3] As RH increases, the ability to sweat decreases and, with low air movement, evaporation is reduced resulting in increased body temperature.[1,3] Exposure to an inhospitable environment for extended periods of time increases the possibility of heat illness such as heat exhaustion and heat stroke.[1] Little can be done to change environmental factors during physical activity, so behavior and activity adjustments are commonly utilized to decrease overall heat stress.[1,2,4]

The wet blub globe temperature index (WBGT) which combines ambient dry temperature (T_{db}) and wet bulb (T_{wb}) measurements with black globe temperature (T_{gt}), was created in the 1950's to assess environmental conditions and limit outbreaks of serious heat illnesses during United States military training camps.[1] Heat index (HI) was subsequently created to evaluate environmental conditions using only T_{db} and RH.[5] These tools aid in the evaluation of the environment to determine appropriate parameters for safe athletic participation with reduced risk of heat illness.[1,2,4] The National Athletic Trainers' Association (NATA)[2] and National Oceanic and Atmospheric Administration's National Weather Service (NWS)[5] provide varying recommendations for activity and rest-break guidelines based on WBGT and HI in order to prevent heat illnesses. However, some limitations do exist when using heat indices including not accounting for sweat evaporation variations, technical error and equipment expenses as well as the inability of HI to account for solar radiation and wind speed.[1,4,6-11] Perhaps the most important

limitation is the presence of microclimates that may obviate the use of regional environmental data in determining activity modifications from available weather indices.

Microclimates are local weather patterns that differ in temperature, humidity, solar radiation and wind speeds from their surrounding region.[12] These differences are primarily caused by the varying amounts of heat or water trapped near the surface in that area.[12] Environmental changes that may occur in microclimates include an increase in heat energy, a decrease in water causing a drier environment, or an increase in wind, removing heat and water vapor from the area, creating a cooler environment.[12] Therefore, temperatures and humidity from a single central weather station of a city may over- or under-estimate conditions of the local climate due to the presence of microclimates.[12-14]

Disagreement exists regarding the most accurate and appropriate method and equipment for environmental evaluation. Previous studies[7,8,10,11,15] have shown that using T_{db}, RH, solar radiation and wind velocity collected by NOAA meteorological stations may be sufficient to determine appropriate activity modifications.[5,7,8,10,11,13,15] However, significant differences in weather condition estimations, which may lead to clinical differences in activity modifications, have also been reported due to the presence of microclimates.[9] The topography of the Hawaiian islands suggest the possibility of microclimates, which may create environmental differences for locations in close proximity and affect recommendations for activity modifications. To our knowledge, no studies examining the evaluation of environmental conditions relative to activity modification recommendations have been conducted in Hawai‘i. Therefore, the purpose of this study is two-fold: 1) to compare environmental data obtained by an on-site heat stress monitor at secondary schools in Hawai‘i to regional meteorological station data from NOAA and 2) to

compare activity modification recommendations based on the collected WBGT and HI values from each location.

METHODS

Research Design

This descriptive study compared environmental data using two different data collection methods: 1) on-site heat stress monitors and 2) National Oceanic and Atmospheric Administration's National Climatic Data Center (NCDC) and NWS websites. The environmental data collected were compared to determine the affect microclimates have on determining activity modifications in Hawai‘i's secondary schools.

Instruments

The Kestrel 4600 (Kestrel 4600 Pro Heat Stress Tracker; Nielsen-Kellerman, Boothwyn, PA) or the Kestrel 5400 (Kestrel 5400 Pro Heat Stress Tracker; Nielsen-Kellerman, Boothwyn, PA) were used to obtain on-site environmental data. Choice of device was dependent on the availability of the device to each secondary school's athletic trainer (AT) and no difference between devices were reported, therefore, both models were used for this study and referred to as "Kestrel meter". Environmental data collected by the Kestrel meters included T_{db}, T_{wb}, RH, T_{gt}, HI and WBGT. Athletic trainers were instructed to mount the Kestrel meter on a tripod 1.2 meters above the ground in accordance with manufacturer's recommendations (Nielsen-Kellerman, Boothwyn, PA). Meteorological data were obtained in one of two ways from the NOAA: 1) monthly through the NCDC archived data[16] or 2) daily through the NWS website.[17]

Participants

Of the 60 of secondary schools in Hawai‘i with ATs and outdoor fall athletics, thirty-three secondary schools had access to a Kestrel meter and agreed to participate in the study (Appendix A).

Procedures

Data collection for Kestrel Meter Measurements. Athletic trainers were instructed to collect data every hour of outdoor athletic activity between 12:00 PM and 8:00 PM on Monday through Saturday, from May through September as possible during athletic activities. The Kestrel meter was set up near the area of activity being conducted for each secondary school. For this study, the following data points were of importance: the measured T_{db}, T_{wb} and RH and the calculated HI and WBGT.

Data collection for Data from the NCDC and NWS. Data from the NCDC were collected retrospectively by selecting the state, meteorological station, month and date from the NCDC Data Access website.[16] In the case of Wheeler Air Force Base where all environmental data were not archived by the NCDC monthly, daily environmental data were collected from the NWS website[17] by entering "Wheeler Air Force Base" in the search bar and using the "3 day history" link provided on that website. The following data points were collected for the local meteorological stations nearest to the secondary school based on school zip code: T_{db}, T_{wb}, HI and RH (Appendix A). Wet bulb temperature data for Wheeler Air Force Base were not published and therefore were estimated using a sling psychrometer nomogram[18] given T_{db} and RH. Since WBGT was not recorded by the NOAA (NCDC or NWS) for any meteorological station, WBGT were calculated using data provided by the NOAA via the following equation:

$$WBGT_{modified} = (T_{wb} \times 0.7) + (T_{db} \times 0.3)$$

where T_{wb} was the wet bulb temperature and T_{db} was the dry bulb temperature in degrees Fahrenheit recorded at the meteorological station.[13,15,16]

Heat index data also were not archived by the NCDC and therefore were calculated using T_{db} and RH measurements applied to the standard HI Chart (Appendix C) or calculated using the NWS Heat Index Calculator provided on the NWS website.[19]

Data collection for Activity Modification Recommendations. The on-site WBGT collected at each secondary school were applied to the Georgia High School Athletic Association WBGT Activity/Rest Break Guidelines as referenced in the most recent NATA Position Statement on Exertional Heat Illnesses[2] to determine the WBGT flag category based on suggested activity modifications (Appendix B). Heat index values were also applied to the HI Chart provided by the NWS and NATA to determine HI flag categories (Appendix C).[20]

Comparison of Kestrel Meter and NOAA Data. Hourly data collected from the NOAA were analyzed and compared to the hourly Kestrel meter data collected at the secondary schools in Hawai'i. Data collected on-site were organized by location, month and hour to determine the number of days per hour per month data were recorded on-site. Data recorded between the hour was associated with the closest full hour, for example, data recorded at 3:29 PM was analyzed with data from 3:00 PM whereas data recorded at 3:30 PM was analyzed with data from 4:00 PM. Hours with less than five days of data per secondary school were not analyzed.

The remaining hours per secondary school were individually compared to NOAA data to determine if collection of on-site data were recommended for that hour. Flag category differences were given priority in determining if on-site data collection should be recommended over significant differences between actual WBGT and HI values since a statistically significant difference between WBGT and HI may not indicate a clinically significant difference based on flag category. If either WBGT flag categories or HI flag categories were different between the secondary school and the associated meteorological station more than 50% of days, it was

recommended for that hour, on-site data be collected regardless of the differences in HI and WBGT between locations. If neither flag categories were different between the secondary school and its associated meteorological station more than 50% of days, on-site data collection was not recommended for that hour. Secondary schools with no hours recommended for on-site environmental readings were categorized as "no recommendation" for on-site data collection. Secondary schools with at least one hour but less than 25% of hours with recommendations were categorized as Recommended, schools with 25% to 50% of hours with recommendations were categorized as Moderately Recommended and schools with more than 50% of hours with recommendations were categorized as Strongly Recommended for on-site data collection.

Determination of WBGT Equation. The WBGT calculated by the Kestrel meter used the following equation:

$$WBGT = (T_{wb} \times 0.7) + (T_{gt} \times 0.2) + (T_{db} \times 0.1)$$

where T_{wb} was wet bulb temperature, T_{gt} was globe temperature and T_{db} was dry bulb temperature in degrees Fahrenheit. To determine the WBGT equation appropriate for each secondary school, similarities in flag categories were analyzed. Flag categories were determined using WBGT values calculated using the WBGT and $WBGT_{modified}$ equations. If the flag category differed more than or equal to 50% of the data points analyzed, it was determined that the WBGT equation was most accurate for that secondary school. If the flag category differed less than 50% of data points analyzed, it was determined that the $WBGT_{modified}$ equation was adequate for that secondary school.

Statistical Analysis

Data collected by the Kestrel meter were compared to data provided by the NOAA. Hourly means of T_{db}, T_{wb}, RH, HI and WBGT values were analyzed using SPSS version 24.0. Multiple

one-way repeated measures analyses of variance were used to compare the hourly means between the Kestrel meter data and the meteorological station data. Alpha level was set at $P<0.05$. Flag categories derived from both HI and WBGT were also compared per hour.

RESULTS

Of the thirty-three secondary schools that agreed to participate, ten schools were removed due to insufficient data, therefore, twenty-three schools remained for analysis (Appendix A). The twenty-three schools were from four of the Hawaiian Islands and were distributed as follows: on O‘ahu, 12 were in the Honolulu International Airport region, one in the Kalaeloa Airport region, two in the Kāne‘ohe Marine Corps Air Station region and one in the Wheeler Air Force Base region; on the Island of Hawai‘i, one in the Kona International Airport at Keāhole region; on Maui, three in the Kahului Airport region and one in the Kapalua Airport region; on Kaua‘i, one in the Lihue Airport region and one in the Kekaha Barking Sands Pacific Missile Range Facility Airport region.

Twenty-two of the twenty-three schools (96%) in Hawai‘i were given the recommendation for on-site environmental data collection based on differing HI and WBGT flag category classifications greater than 50% of days between meteorological station and on-site data and significant differences in HI ($P<0.001$), WBGT ($P<0.001$) (Tables 1-4,6,8,9,11, and 12). The remaining school was not given a recommendation for on-site data collection which suggested reliance on NOAA meteorological station data were sufficient to provide accurate environmental data to determine appropriate activity modifications. Of the twenty-two schools given recommendations, fourteen secondary schools were categorized as Strongly Recommended, five as Moderately Recommended and two as Recommended for collection of on-site environmental data. One secondary school’s recommendation for on-site collection of environmental data could not be categorized due to error in reporting of WBGT data.

Flag categories based on data from the NOAA for HI were underestimated 65.1% (639/981) of days analyzed and WBGT were underestimated 99.1% (924/932) of days compared

to those derived from on-site readings (Table 14). The majority of underestimations were by one flag category for HI (62.4%; 612/981) and WBGT (74.6%; 695/932). Flag categories were underestimated by two categories for WBGT 20.2% (188/932) of days analyzed while HI were underestimated by two categories only 2.7% (26/981) of days.

Additionally, WBGT flag categories based on WBGT and $WBGT_{modified}$ equations were compared to determine which equation was most accurate for each secondary school that was given a recommendation for on-site data collection. Differences between equations indicated the need to use WBGT for nine secondary schools (45%; 9/20) based on flag category differences occurring more than 50% of days analyzed. The use of $WBGT_{modified}$ equation was determined to be adequate for eleven secondary schools (55%; 11/20) based on less than 50% of days analyzed having different flag categories when using this equation. Two schools did not provide enough data to accurately compare WBGT equations. Flag categories for the secondary schools can be found in tables 5, 7, 10 and 13.

Table 1. Secondary Schools and Honolulu International Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
ʻAiea High School											
	July	3:00 PM	7	86.29 ± 2.21	90.29 ± 4.48	0.06	71.43%	76.20 ± 1.37	79.75 ± 7.15	0.22	28.57%
	August	4:00 PM	10	88.40 ± 1.26	92.71 ± 3.78	0.00 *	55.56%	77.15 ± 0.76	85.21 ± 2.31	0.00 *	90.00%
Kula Kaiapuni 'O Ānuenue											
	August	3:00 PM	6	89.33 ± 1.97	80.21 ± 5.44	0.00 *	83.33%	77.43 ± 1.43	77.63 ± 7.68	0.95	33.33%
		4:00 PM	11	87.36 ± 1.80	80.83 ± 5.47	0.00 *	63.64%	76.41 ± 1.26	79.09 ± 3.34	0.02 *	18.18%
		5:00 PM	11	86.27 ± 2.45	80.29 ± 6.46	0.01 *	81.82%	76.25 ± 1.44	76.18 ± 2.61	0.94	0.00%
		6:00 PM	5	84.40 ± 0.89	79.48 ± 5.96	0.11	60.00%	75.02 ± 0.68	73.40 ± 3.59	0.35	0.00%
	September	4:00 PM	6	87.15 ± 2.11	84.65 ± 5.50	0.32	33.33%	76.35 ± 1.42	79.31 ± 3.47	0.08	16.67%
Damien Memorial School											
	August	2:00 PM	5	90.00 ± 3.08	93.20 ± 3.40	0.16	40.00%	77.58 ± 2.02	84.76 ± 1.27	0.00 *	100.00%
		3:00 PM	10	89.40 ± 1.71	93.64 ± 4.42	0.01 *	30.00%	77.59 ± 1.24	85.33 ± 2.03	0.00 *	100.00%
		4:00 PM	13	88.62 ± 2.43	92.23 ± 4.88	0.02 *	53.85%	77.25 ± 1.40	84.08 ± 3.02	0.00 *	69.23%
		5:00 PM	13	87.08 ± 2.29	89.77 ± 3.69	0.03 *	30.77%	76.65 ± 1.42	80.92 ± 2.82	0.00 *	53.85%
	September	2:00 PM	4	86.65 ± 2.90	92.43 ± 3.98	0.06	50.00%	76.15 ± 1.61	85.53 ± 1.73	0.00 *	100.00%
		3:00 PM	6	86.23 ± 1.96	89.05 ± 8.10	0.43	83.33%	75.78 ± 1.09	80.90 ± 8.00	0.15	66.67%
		4:00 PM	6	86.10 ± 1.70	84.53 ± 7.91	0.64	33.33%	75.67 ± 1.19	76.90 ± 7.79	0.71	20.00%
		5:00 PM	6	84.69 ± 1.71	83.83 ± 4.18	0.65	16.67%	74.98 ± 1.03	75.58 ± 3.23	0.67	0.00%
Farrington High School											
	August	4:00 PM	5	87.80 ± 1.30	92.70 ± 5.74	0.10	40.00%	76.68 ± 0.79	82.98 ± 4.06	0.01 *	80.00%
		5:00 PM	12	86.50 ± 2.61	94.81 ± 7.23	0.00 *	66.67%	76.32 ± 1.59	83.56 ± 4.40	0.00 *	66.67%
		6:00 PM	12	84.92 ± 2.19	89.98 ± 5.78	0.01 *	33.33%	75.51 ± 1.43	79.19 ± 3.56	0.00 *	16.67%
	September	4:00 PM	7	86.94 ± 1.98	90.11 ± 2.52	0.02 *	42.86%	76.24 ± 1.44	80.16 ± 2.95	0.01 *	14.29%
		5:00 PM	9	85.52 ± 1.53	90.66 ± 4.74	0.01 *	44.44%	75.54 ± 1.11	81.78 ± 3.22	0.00 *	55.56%
		6:00 PM	9	83.61 ± 1.84	85.86 ± 2.33	0.04 *	11.11%	74.70 ± 1.50	76.32 ± 2.06	0.08	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 1. (Continued) Secondary Schools and Honolulu International Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
‘Iolani School											
	August	3:00 PM	9	89.33 ± 2.12	95.43 ± 3.39	0.00 *	44.44%	77.52 ± 1.29	86.31 ± 2.06	0.00 *	100.00%
		4:00 PM	13	88.54 ± 2.67	91.51 ± 2.10	0.00 *	61.54%	77.07 ± 1.54	84.97 ± 2.03	0.00 *	92.31%
		5:00 PM	6	85.17 ± 1.47	91.40 ± 2.93	0.00 *	83.33%	75.43 ± 0.81	84.90 ± 1.23	0.00 *	100.00%
	September	3:00 PM	20	86.76 ± 2.96	90.51 ± 3.64	0.00 *	40.00%	76.31 ± 1.60	84.35 ± 2.57	0.00 *	95.00%
Kaimuki High School											
	August	2:00 PM	6	89.17 ± 1.33	89.38 ± 6.28	0.94	50.00%	77.18 ± 1.21	79.63 ± 6.15	0.36	33.33%
		3:00 PM	9	88.89 ± 1.17	91.33 ± 4.51	0.13	66.67%	77.46 ± 0.94	83.46 ± 2.65	0.00 *	88.89%
	September	2:00 PM	10	88.14 ± 2.72	89.83 ± 3.28	0.23	30.00%	76.61 ± 1.49	78.08 ± 2.73	0.15	10.00%
		3:00 PM	7	87.81 ± 3.32	92.36 ± 3.80	0.03 *	42.86%	76.97 ± 1.45	82.97 ± 0.86	0.00 *	85.71%
Kaiser High School											
	August	5:00 PM	7	86.00 ± 2.00	89.56 ± 1.51	0.00 *	57.14%	76.09 ± 1.12	82.06 ± 2.71	0.00 *	57.14%
		6:00 PM	9	84.56 ± 1.13	86.22 ± 2.02	0.05 *	11.11%	75.37 ± 0.73	76.86 ± 1.01	0.00 *	0.00%
		7:00 PM	5	81.40 ± 1.95	84.64 ± 2.11	0.04 *	20.00%	74.08 ± 1.30	75.74 ± 1.54	0.10	0.00%
	September	5:00 PM	6	83.84 ± 1.68	85.60 ± 1.45	0.08	0.00%	74.43 ± 1.04	78.63 ± 2.90	0.01 *	0.00%
		6:00 PM	7	82.51 ± 2.29	84.09 ± 1.92	0.19	14.29%	74.14 ± 1.52	75.07 ± 1.26	0.24	0.00%
Kalani High School											
	August	1:00 PM	5	88.40 ± 1.14	91.69 ± 2.71	0.04 *	60.00%	76.62 ± 0.57	83.19 ± 7.67	0.09	60.00%
		2:00 PM	18	89.28 ± 2.11	95.05 ± 6.67	0.00 *	72.22%	77.38 ± 1.23	86.67 ± 4.96	0.00 *	88.89%
		3:00 PM	20	89.25 ± 1.62	98.29 ± 4.87	0.00 *	65.00%	77.43 ± 1.03	87.87 ± 2.48	0.00 *	100.00%
		4:00 PM	20	88.65 ± 1.93	94.62 ± 7.09	0.00 *	60.00%	77.16 ± 1.18	85.94 ± 3.63	0.00 *	90.00%
		5:00 PM	20	86.90 ± 2.27	93.63 ± 4.23	0.00 *	75.00%	76.41 ± 1.40	83.36 ± 3.12	0.00 *	70.00%
		6:00 PM	13	85.15 ± 1.77	89.54 ± 4.45	0.00 *	30.77%	75.54 ± 1.23	79.70 ± 2.55	0.00 *	7.69%
		7:00 PM	6	82.67 ± 1.75	82.94 ± 1.35	0.77	0.00%	74.68 ± 0.68	74.90 ± 0.65	0.58	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage

*=Significantly different than MS

Table 1. (Continued) Secondary Schools and Honolulu International Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Kalani High School (Continued)											
	September	1:00 PM	4	84.31 ± 7.73	90.82 ± 5.66	0.22	100.00%	76.20 ± 1.29	82.76 ± 5.52	0.06	50.00%
		2:00 PM	9	87.91 ± 3.02	95.26 ± 4.21	0.00 *	77.78%	76.39 ± 1.88	87.62 ± 2.21	0.00 *	100.00%
		3:00 PM	13	87.06 ± 3.21	94.81 ± 4.22	0.00 *	61.54%	76.47 ± 1.58	86.55 ± 2.78	0.00 *	92.31%
		4:00 PM	14	86.76 ± 1.88	92.63 ± 3.07	0.00 *	71.43%	76.10 ± 1.20	84.71 ± 3.34	0.00 *	71.43%
		5:00 PM	12	86.17 ± 1.20	93.01 ± 6.18	0.00 *	50.00%	75.81 ± 0.89	82.34 ± 3.70	0.00 *	66.67%
		6:00 PM	9	83.89 ± 1.62	86.54 ± 3.02	0.03 *	44.44%	74.84 ± 1.33	77.76 ± 2.23	0.00 *	22.22%
McKinley High School											
	August	3:00 PM	6	89.00 ± 0.89	96.20 ± 2.53	0.00 *	66.67%	77.23 ± 0.63	87.89 ± 1.48	0.00 *	100.00%
		4:00 PM	16	88.44 ± 2.28	95.66 ± 4.28	0.00 *	75.00%	77.11 ± 1.31	85.98 ± 2.06	0.00 *	93.75%
		5:00 PM	16	86.69 ± 1.96	94.53 ± 5.11	0.00 *	68.75%	76.42 ± 1.21	83.19 ± 3.68	0.00 *	62.50%
		6:00 PM	14	85.14 ± 1.66	89.41 ± 4.15	0.00 *	21.43%	75.67 ± 1.05	79.37 ± 2.49	0.00 *	21.43%
	September	3:00 PM	9	86.54 ± 2.80	89.82 ± 3.10	0.03 *	55.56%	75.89 ± 1.79	81.06 ± 5.89	0.02 *	55.56%
		4:00 PM	16	85.84 ± 1.80	93.35 ± 5.74	0.00 *	62.50%	75.51 ± 1.01	82.48 ± 3.65	0.00 *	68.75%
		5:00 PM	15	84.77 ± 1.53	88.69 ± 2.92	0.00 *	40.00%	75.10 ± 0.98	80.96 ± 2.90	0.00 *	40.00%
		6:00 PM	16	82.81 ± 1.88	84.62 ± 1.99	0.01 *	0.00%	74.18 ± 1.33	75.49 ± 1.77	0.02 *	0.00%
		7:00 PM	4	81.47 ± 1.08	82.00 ± 1.72	0.63	25.00%	73.48 ± 0.74	73.54 ± 0.65	0.91	0.00%
Mid Pacific											
	July	3:00 PM	6	86.67 ± 2.88	93.70 ± 6.93	0.04 *	50.00%	76.87 ± 1.38	83.38 ± 4.61	0.01 *	66.67%
		4:00 PM	7	85.71 ± 2.81	99.56 ± 22.48	0.13	57.14%	76.09 ± 1.31	84.03 ± 7.38	0.02 *	57.14%
		5:00 PM	7	85.14 ± 1.46	89.69 ± 4.64	0.03 *	57.14%	75.64 ± 1.05	80.79 ± 3.91	0.01 *	42.86%
		6:00 PM	8	85.00 ± 3.46	89.79 ± 7.78	0.13	37.50%	75.61 ± 1.62	80.99 ± 4.81	0.01 *	50.00%
	August	2:00 PM	7	89.86 ± 2.67	91.56 ± 3.55	0.33	14.29%	77.80 ± 1.64	85.29 ± 4.70	0.00 *	71.43%
		3:00 PM	11	89.18 ± 1.94	92.58 ± 4.42	0.03 *	54.55%	77.53 ± 1.30	86.51 ± 2.68	0.00 *	100.00%
		4:00 PM	12	89.08 ± 2.27	93.53 ± 7.15	0.05	33.33%	77.50 ± 1.35	85.94 ± 2.93	0.00 *	91.67%
		5:00 PM	12	87.33 ± 2.35	92.34 ± 10.19	0.11	25.00%	76.76 ± 1.52	81.92 ± 4.03	0.00 *	41.67%
		6:00 PM	11	85.45 ± 2.11	88.06 ± 4.59	0.10	36.36%	75.93 ± 1.44	80.05 ± 3.84	0.00 *	36.36%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 1. (Continued) Secondary Schools and Honolulu International Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Mid Pacific (Continued)											
	September	3:00 PM	14	86.77 ± 2.60	93.89 ± 18.15	0.16	42.86%	75.86 ± 1.54	85.07 ± 4.59	0.00 *	85.71%
		4:00 PM	16	86.25 ± 2.19	89.18 ± 4.57	0.03 *	25.00%	75.74 ± 1.39	82.94 ± 3.56	0.00 *	56.25%
		5:00 PM	16	85.00 ± 1.93	88.11 ± 3.00	0.00 *	31.25%	75.22 ± 1.17	80.85 ± 3.04	0.00 *	37.50%
		6:00 PM	14	82.31 ± 1.93	84.86 ± 2.24	0.00 *	14.29%	73.87 ± 1.37	76.81 ± 2.55	0.00 *	0.00%
Moanalua High School											
	July	4:00 PM	5	87.00 ± 3.08	85.82 ± 8.76	0.78	80.00%	76.38 ± 1.38	76.89 ± 7.94	0.89	40.00%
		5:00 PM	4	85.75 ± 2.06	89.65 ± 4.81	0.19	50.00%	76.20 ± 1.09	82.13 ± 6.30	0.11	50.00%
		6:00 PM	4	84.75 ± 4.50	89.20 ± 3.10	0.15	75.00%	75.88 ± 1.43	79.07 ± 3.51	0.14	25.00%
	August	3:00 PM	8	89.38 ± 1.85	93.61 ± 10.48	0.28	25.00%	77.50 ± 1.24	84.90 ± 5.28	0.00 *	87.50%
		4:00 PM	17	88.29 ± 2.28	92.23 ± 4.23	0.00 *	52.94%	76.89 ± 1.47	84.57 ± 2.52	0.00 *	82.35%
		5:00 PM	16	86.69 ± 2.30	90.42 ± 3.09	0.00 *	50.00%	76.34 ± 1.33	83.15 ± 2.27	0.00 *	81.25%
		6:00 PM	13	85.92 ± 3.04	86.44 ± 2.60	0.64	15.38%	75.93 ± 1.65	77.03 ± 2.21	0.16	7.69%
	September	4:00 PM	6	85.45 ± 2.35	90.83 ± 3.24	0.01 *	50.00%	75.35 ± 1.24	82.76 ± 3.36	0.00 *	50.00%
		5:00 PM	8	84.32 ± 1.76	89.80 ± 2.60	0.00 *	25.00%	74.78 ± 1.03	81.28 ± 2.52	0.00 *	37.50%
		6:00 PM	4	81.29 ± 1.69	83.80 ± 2.14	0.12	0.00%	73.13 ± 1.35	75.02 ± 1.12	0.07	0.00%
		7:00 PM	4	80.11 ± 1.14	79.21 ± 8.38	0.84	25.00%	72.93 ± 1.26	73.13 ± 3.17	0.91	0.00%
Saint Louis School											
	June	3:00 PM	5	87.20 ± 1.92	89.66 ± 5.82	0.40	20.00%	75.90 ± 1.18	78.24 ± 2.44	0.09	0.00%
		4:00 PM	7	85.71 ± 1.80	88.63 ± 5.91	0.24	42.86%	75.47 ± 1.05	77.20 ± 1.83	0.05	0.00%
	July	3:00 PM	5	86.00 ± 2.00	94.08 ± 3.96	0.00 *	80.00%	76.34 ± 0.84	80.22 ± 3.08	0.03 *	20.00%
		4:00 PM	11	87.09 ± 2.51	92.12 ± 4.42	0.00 *	54.55%	76.15 ± 1.35	81.26 ± 4.39	0.00 *	27.27%
		5:00 PM	8	86.13 ± 2.10	90.13 ± 4.98	0.06	50.00%	75.95 ± 1.46	78.36 ± 2.16	0.02 *	0.00%
		6:00 PM	4	86.75 ± 2.36	87.40 ± 3.63	0.77	25.00%	76.35 ± 1.56	78.05 ± 2.10	0.24	0.00%
	August	2:00 PM	9	89.67 ± 2.45	94.99 ± 3.71	0.00 *	44.44%	77.68 ± 1.34	85.88 ± 3.01	0.00 *	100.00%
		3:00 PM	9	89.22 ± 1.30	93.88 ± 2.81	0.00 *	66.67%	77.14 ± 0.69	83.51 ± 3.02	0.00 *	44.44%
		4:00 PM	7	88.29 ± 0.95	93.04 ± 6.20	0.07	71.43%	76.97 ± 0.59	84.16 ± 2.27	0.00 *	85.71%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 2. Secondary Schools and Kalaeloa Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Campbell High School											
	July	4:00 PM	5	90.00 ± 3.39	89.17 ± 6.44	0.06	0.00%	77.60 ± 1.82	79.84 ± 1.85	0.09	0.00%
	August	4:00 PM	10	91.20 ± 3.01	93.09 ± 4.41	0.28	30.00%	78.45 ± 1.44	80.96 ± 2.83	0.02 *	30.00%
		5:00 PM	7	90.14 ± 2.19	91.71 ± 4.00	0.38	57.14%	77.94 ± 1.30	79.60 ± 1.52	0.05 *	14.29%
		6:00 PM	6	87.33 ± 2.66	88.49 ± 4.78	0.62	16.67%	76.43 ± 1.89	78.41 ± 1.31	0.06	0.00%
		7:00 PM	4	85.00 ± 2.16	84.65 ± 4.07	0.88	25.00%	75.83 ± 1.93	76.60 ± 2.08	0.61	0.00%
	September	5:00 PM	5	88.33 ± 2.21	90.28 ± 4.03	0.37	0.00%	76.88 ± 1.28	79.09 ± 2.73	0.14	20.00%
		6:00 PM	4	86.67 ± 2.56	86.90 ± 0.53	0.87	25.00%	76.73 ± 0.88	77.77 ± 1.28	0.23	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 3. Secondary School and Wheeler Air Force Base Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Wai‘anae High School											
	July	4:00 PM	4	83.75 ± 6.60	89.65 ± 7.78	0.29	75.00%	No data	No data	No data	No data
		5:00 PM	4	83.50 ± 4.20	91.99 ± 1.89	0.01 *	100.00%	No data	No data	No data	No data
		6:00 PM	4	82.50 ± 4.80	92.03 ± 3.21	0.02 *	100.00%	No data	No data	No data	No data
	August	4:00 PM	13	85.08 ± 1.50	94.79 ± 4.19	0.00 *	0.00%	No data	No data	No data	No data
		5:00 PM	16	83.75 ± 2.32	91.75 ± 4.78	0.00 *	6.25%	No data	No data	No data	No data
		6:00 PM	14	81.57 ± 2.10	91.07 ± 2.66	0.00 *	21.43%	No data	No data	No data	No data
		7:00 PM	6	77.83 ± 0.75	86.09 ± 1.08	0.00 *	100.00%	No data	No data	No data	No data

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 4: Secondary Schools and Kāneʻohe Marine Corps Air Station Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Castle High School											
	July	3:00 PM	4	89.25 ± 1.71	95.45 ± 2.31	0.06	50.00%	78.25 ± 0.84	85.55 ± 2.36	0.00 *	100.00%
		4:00 PM	5	88.60 ± 1.14	93.70 ± 5.56	0.08	40.00%	77.88 ± 0.65	85.14 ± 3.48	0.00 *	80.00%
		5:00 PM	6	87.33 ± 1.97	86.81 ± 2.89	0.72	16.67%	77.13 ± 1.58	79.85 ± 3.02	0.08	16.67%
		6:00 PM	5	85.20 ± 1.30	86.11 ± 2.20	0.45	0.00%	76.80 ± 1.11	80.46 ± 2.90	0.03 *	20.00%
	August	4:00 PM	9	87.78 ± 1.79	89.44 ± 6.68	0.48	55.56%	77.28 ± 0.79	81.14 ± 5.84	0.07	55.56%
		5:00 PM	12	86.58 ± 1.44	87.70 ± 3.40	0.31	16.67%	76.83 ± 0.68	79.24 ± 2.59	0.01 *	8.33%
		6:00 PM	9	83.78 ± 3.49	85.70 ± 1.56	0.15	11.11%	75.99 ± 1.59	79.76 ± 3.77	0.01 *	22.22%
	September	4:00 PM	9	85.73 ± 1.34	88.20 ± 3.01	0.04 *	33.33%	76.29 ± 1.18	80.64 ± 2.69	0.00 *	33.33%
		5:00 PM	11	84.51 ± 1.73	84.79 ± 1.28	0.68	0.00%	75.88 ± 1.21	78.08 ± 2.05	0.01 *	9.09%
		6:00 PM	7	82.92 ± 1.46	83.33 ± 1.42	0.61	57.14%	75.06 ± 1.00	76.82 ± 3.09	0.18	14.29%
Kailua High School											
	August	4:00 PM	4	87.75 ± 1.71	87.49 ± 0.81	0.79	25.00%	77.60 ± 0.91	78.53 ± 3.48	0.62	25.00%
		5:00 PM	7	88.00 ± 2.52	88.85 ± 3.61	0.62	14.29%	77.73 ± 1.10	80.68 ± 3.38	0.05 *	28.57%
	September	4:00 PM	5	84.55 ± 3.00	85.68 ± 2.26	0.52	0.00%	75.76 ± 1.92	78.15 ± 3.73	0.24	20.00%
		5:00 PM	12	84.34 ± 1.56	84.25 ± 2.29	0.90	0.00%	75.67 ± 1.11	76.87 ± 2.44	0.14	0.00%
		6:00 PM	8	83.02 ± 1.81	83.03 ± 1.97	0.99	12.50%	75.06 ± 1.14	75.07 ± 1.33	1.00	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 5. Comparison of Secondary School Environmental Data to Meteorological Stations on Oʻahu

Location	Distance to MS (miles)	On-Site Data Recommended	Rating of Recommendation	WBGT Equation
Honolulu International Airport (HNL)				
ʻAiea High School	4.20	Yes	Strongly Recommended	WBGT
Kula Kaiapuni 'O Ānuenue	8.83	Yes	Strongly Recommended	WBGTmodified
Damien Memorial School	3.69	Yes	Strongly Recommended	WBGT
Farrington High School	3.41	Yes	Moderately Recommended	WBGTmodified
ʻIolani School	7.21	Yes	Strongly Recommended	N/A
Kaimukī High School	7.60	Yes	Strongly Recommended	WBGT
Kaiser High School	15.00	Yes	Recommended	WBGTmodified
Kalani High School	10.33	Yes	Strongly Recommended	WBGT
McKinley High School	5.38	Yes	Strongly Recommended	WBGT
Mid Pacific	7.18	Yes	Strongly Recommended	WBGT
Moanalua High School	2.00	Yes	Strongly Recommended	WBGT
Saint Louis School	8.06	Yes	Strongly Recommended	WBGTmodified
Kalaeloa Airport (JRF)				
Campbell High School	4.02	Yes	Recommended	WBGTmodified
Wheeler Air Force Base (WAFB)				
Waiʻanae High School	10.82	Yes	N/A	N/A
Kāneʻohe Marine Corps Air Station (KMCAS)				
Castle High School	3.61	Yes	Moderately Recommended	WBGTmodified
Kailua High School	3.08	No	N/A	N/A

MS=Meteorological station, WBGT=Wet bulb globe temperature index, WBGTmodified=Modified wet bulb globe temperature index, N/A=Not available

Table 6. Secondary School and Kona International Airport at Keāhole Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Konawaena High School											
	May	2:00 PM	6	86.17 ± 3.06	74.75 ± 1.39	0.06	100.00%	76.32 ± 1.63	71.87 ± 2.22	0.00 *	0.00%
		3:00 PM	14	85.64 ± 3.37	74.31 ± 3.03	0.00 *	84.62%	76.30 ± 1.13	72.38 ± 3.37	0.00 *	0.00%
		4:00 PM	14	84.29 ± 3.91	72.86 ± 2.26	0.00 *	92.86%	75.65 ± 1.51	70.73 ± 2.71	0.00 *	0.00%
		5:00 PM	13	83.23 ± 2.95	72.18 ± 2.27	0.00 *	84.62%	75.22 ± 0.93	69.67 ± 1.95	0.00 *	0.00%
		6:00 PM	5	83.80 ± 1.10	72.56 ± 1.77	0.00 *	100.00%	75.28 ± 0.75	69.84 ± 1.27	0.00 *	0.00%
	August	2:00 PM	8	95.75 ± 3.65	80.60 ± 3.42	0.00 *	100.00%	80.75 ± 1.41	75.79 ± 5.42	0.03 *	62.50%
		3:00 PM	8	95.00 ± 3.78	79.55 ± 3.77	0.00 *	100.00%	80.29 ± 1.35	77.50 ± 6.44	0.25	12.50%
		4:00 PM	8	94.50 ± 2.20	77.38 ± 2.60	0.00 *	100.00%	80.25 ± 0.88	73.95 ± 1.98	0.00 *	0.00%
		5:00 PM	8	94.00 ± 1.93	78.33 ± 3.36	0.00 *	100.00%	79.84 ± 0.69	73.80 ± 1.86	0.00 *	0.00%
		6:00 PM	9	92.11 ± 1.54	78.74 ± 3.39	0.00 *	100.00%	79.37 ± 0.65	74.73 ± 3.64	0.00 *	11.11%
	September	6:00 PM	19	88.78 ± 2.42	78.49 ± 4.47	0.00 *	89.47%	77.72 ± 1.33	73.55 ± 2.29	0.00 *	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 7. Comparison of Secondary School Environmental Data to Meteorological Station on the Island of Hawai‘i

Location	Distance to MS (miles)	On-Site Data Recommended	Rating of Recommendation	WBGT Equation
Kona International Airport at Keāhole (KOA)				
Konawaena High School	17.85	Yes	Strongly Recommended	WBGTmodified

MS=Meteorological station, WBGT=Wet bulb globe temperature index, WBGTmodified=Modified wet bulb globe temperature index

Table 8. Secondary School and Kahului International Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Baldwin High School											
	May	2:00 PM	9	84.22 ± 4.87	82.93 ± 6.28	0.06	11.11%	75.21 ± 2.08	78.26 ± 5.22	0.12	22.22%
		3:00 PM	9	84.00 ± 3.97	83.13 ± 6.31	0.73	22.22%	75.02 ± 1.84	77.73 ± 4.86	0.14	22.22%
		4:00 PM	10	81.40 ± 4.81	80.95 ± 7.80	0.88	30.00%	73.70 ± 1.95	73.71 ± 2.22	0.99	0.00%
		5:00 PM	10	80.30 ± 5.27	78.42 ± 5.28	0.44	40.00%	73.29 ± 2.28	72.84 ± 2.52	0.68	0.00%
	June	2:00 PM	19	89.00 ± 2.65	88.36 ± 5.06	0.63	36.84%	77.41 ± 1.43	81.44 ± 4.33	0.00 *	42.11%
		3:00 PM	20	88.10 ± 3.11	88.70 ± 6.24	0.70	45.00%	76.97 ± 1.52	81.59 ± 3.32	0.00 *	40.00%
		4:00 PM	19	86.95 ± 3.08	86.35 ± 4.81	0.65	26.32%	76.46 ± 1.57	78.87 ± 4.00	0.02 *	31.58%
		5:00 PM	19	85.68 ± 2.96	82.84 ± 2.55	0.00 *	26.32%	75.72 ± 1.68	75.52 ± 2.17	0.75	0.00%
		6:00 PM	18	82.50 ± 2.50	81.98 ± 2.53	0.54	16.67%	74.38 ± 1.54	74.74 ± 1.66	0.51	0.00%
	July	2:00 PM	17	91.59 ± 3.92	93.51 ± 6.44	0.30	35.29%	78.55 ± 1.67	83.75 ± 4.36	0.00 *	70.59%
		3:00 PM	17	90.59 ± 4.39	92.83 ± 7.66	0.30	29.41%	78.24 ± 1.87	83.46 ± 4.22	0.00 *	58.82%
		4:00 PM	17	90.35 ± 4.33	90.98 ± 6.49	0.74	41.18%	78.06 ± 1.90	80.89 ± 3.77	0.01 *	47.06%
		5:00 PM	17	88.12 ± 3.67	87.92 ± 5.69	0.91	17.65%	77.16 ± 1.73	78.89 ± 4.11	0.12	17.65%
		6:00 PM	16	85.38 ± 2.99	86.24 ± 3.84	0.48	18.75%	75.98 ± 1.46	77.16 ± 2.62	0.13	6.25%
	August	1:00 PM	13	92.85 ± 2.88	93.92 ± 5.44	0.53	15.38%	79.08 ± 1.14	85.00 ± 3.54	0.00 *	92.31%
		2:00 PM	23	93.04 ± 3.59	93.87 ± 6.41	0.59	17.39%	79.23 ± 1.63	83.25 ± 3.50	0.00 *	60.87%
		3:00 PM	23	92.04 ± 2.95	93.16 ± 7.15	0.49	34.78%	78.86 ± 1.30	82.17 ± 3.31	0.00 *	39.13%
		4:00 PM	23	90.43 ± 3.31	89.47 ± 4.41	0.41	17.39%	78.19 ± 1.47	80.47 ± 3.35	0.00 *	34.78%
		5:00 PM	23	88.35 ± 3.55	87.49 ± 4.22	0.46	21.74%	77.34 ± 1.63	77.62 ± 2.25	0.63	8.70%
		6:00 PM	21	85.67 ± 2.15	85.87 ± 2.40	0.77	10.53%	76.11 ± 1.35	76.60 ± 1.30	0.25	0.00%
	September	1:00 PM	17	90.97 ± 3.44	92.57 ± 4.99	0.29	47.37%	78.34 ± 1.30	83.73 ± 3.24	0.00 *	82.35%
		2:00 PM	22	90.01 ± 3.69	91.72 ± 4.15	0.16	36.36%	77.98 ± 1.19	82.88 ± 3.14	0.00 *	72.73%
		3:00 PM	20	89.38 ± 3.12	91.88 ± 5.22	0.07	40.00%	77.71 ± 1.09	81.73 ± 3.03	0.00 *	55.00%
		4:00 PM	21	88.01 ± 3.05	88.39 ± 4.56	0.75	19.05%	76.99 ± 1.50	80.82 ± 4.10	0.00 *	42.86%
		5:00 PM	20	86.21 ± 2.62	85.87 ± 3.09	0.70	25.00%	76.07 ± 1.43	78.05 ± 3.41	0.02 *	15.00%
		6:00 PM	18	83.07 ± 2.25	83.09 ± 2.39	0.98	11.11%	74.81 ± 1.30	75.15 ± 1.49	0.46	0.00%

Table 8. (Continued) Secondary School and Kahului International Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Kamehameha Schools, Maui											
	July	4:00 PM	4	93.75 ± 5.91	87.43 ± 6.85	0.21	25.00%	79.53 ± 2.43	82.83 ± 6.49	0.38	25.00%
		5:00 PM	4	89.75 ± 5.06	87.13 ± 9.90	0.65	75.00%	78.08 ± 1.98	81.88 ± 5.35	0.23	50.00%
	August	4:00 PM	14	90.29 ± 3.34	85.16 ± 3.76	0.00 *	71.43%	78.10 ± 1.37	79.25 ± 2.92	0.19	21.43%
		5:00 PM	5	89.40 ± 1.14	82.94 ± 3.88	0.01 *	40.00%	77.72 ± 0.46	76.84 ± 3.75	0.62	0.00%
		6:00 PM	5	86.80 ± 1.10	82.70 ± 4.79	0.10	60.00%	76.78 ± 0.75	77.80 ± 4.51	0.63	20.00%
	September	4:00 PM	10	87.22 ± 3.85	79.47 ± 3.36	0.00 *	60.00%	76.79 ± 1.78	75.12 ± 4.11	0.25	0.00%
		5:00 PM	11	86.52 ± 3.22	79.05 ± 3.46	0.00 *	81.82%	76.18 ± 1.68	75.35 ± 3.57	0.49	0.00%
		6:00 PM	8	82.72 ± 2.20	76.65 ± 3.46	0.00 *	75.00%	74.49 ± 1.49	72.20 ± 4.67	0.21	0.00%
Maui High School											
	July	2:00 PM	9	93.22 ± 3.73	95.00 ± 4.27	0.36	0.00%	79.36 ± 1.46	85.40 ± 2.38	0.00 *	88.89%
		3:00 PM	12	91.83 ± 4.51	95.94 ± 6.50	0.09	36.36%	78.85 ± 1.80	84.18 ± 3.56	0.00 *	72.73%
		4:00 PM	13	91.54 ± 4.14	91.18 ± 4.55	0.84	27.27%	78.58 ± 1.81	83.38 ± 4.28	0.00 *	72.73%
		5:00 PM	14	88.64 ± 3.84	88.79 ± 4.21	0.93	8.33%	77.49 ± 1.70	81.27 ± 4.17	0.00 *	50.00%
		6:00 PM	14	86.00 ± 2.94	86.65 ± 3.08	0.57	0.00%	76.43 ± 1.38	77.99 ± 2.11	0.03 *	0.00%
	August	2:00 PM	12	93.92 ± 3.58	95.28 ± 6.40	0.53	33.33%	79.61 ± 1.62	84.38 ± 4.03	0.00 *	75.00%
		3:00 PM	17	92.35 ± 2.67	93.32 ± 3.91	0.40	23.53%	79.04 ± 1.19	83.25 ± 2.50	0.00 *	64.71%
		4:00 PM	19	90.79 ± 3.10	91.19 ± 3.73	0.72	58.82%	78.48 ± 1.36	82.39 ± 3.19	0.00 *	70.59%
		5:00 PM	19	88.84 ± 3.39	88.82 ± 2.92	0.98	41.18%	77.65 ± 1.56	79.03 ± 1.87	0.02 *	5.88%
		6:00 PM	19	86.05 ± 2.68	87.03 ± 3.01	0.30	11.76%	76.43 ± 1.52	77.30 ± 1.70	0.10	0.00%
	September	2:00 PM	6	90.79 ± 5.23	92.08 ± 5.13	0.68	16.67%	78.67 ± 1.32	83.90 ± 3.40	0.01 *	83.33%
		3:00 PM	13	89.88 ± 3.40	96.18 ± 10.17	0.04 *	46.15%	77.99 ± 1.19	84.98 ± 4.18	0.00 *	84.62%
		4:00 PM	20	88.34 ± 2.71	91.18 ± 6.33	0.07	40.00%	77.13 ± 1.32	82.28 ± 2.91	0.00 *	65.00%
		5:00 PM	20	86.12 ± 2.68	87.00 ± 3.48	0.38	10.00%	76.02 ± 1.42	78.66 ± 3.09	0.00 *	15.00%
		6:00 PM	15	83.27 ± 2.12	83.95 ± 2.62	0.44	0.00%	74.51 ± 1.32	75.05 ± 1.42	0.28	0.00%
		7:00 PM	9	80.91 ± 2.03	83.51 ± 2.32	0.02 *	11.11%	73.72 ± 1.22	74.69 ± 1.17	0.11	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 9. Secondary School and Kapalua Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Lahainaluna High School											
	August	2:00 PM	10	88.20 ± 5.18	95.36 ± 6.70	0.06	75.00%	77.42 ± 1.96	84.63 ± 5.49	0.00 *	62.50%
		3:00 PM	18	87.56 ± 3.35	97.17 ± 4.04	0.00 *	84.21%	76.84 ± 1.65	86.32 ± 4.32	0.00 *	88.89%
		4:00 PM	19	86.74 ± 3.23	96.77 ± 4.79	0.00 *	84.21%	76.46 ± 1.44	86.92 ± 2.61	0.00 *	100.00%
		5:00 PM	19	85.16 ± 3.18	92.62 ± 3.93	0.00 *	63.16%	75.69 ± 1.76	83.47 ± 3.25	0.00 *	73.68%
		6:00 PM	20	83.20 ± 3.47	90.20 ± 4.08	0.00 *	50.00%	74.73 ± 1.93	80.75 ± 2.42	0.00 *	25.00%
	September	2:00 PM	10	85.21 ± 3.14	92.26 ± 2.46	0.00 *	80.00%	75.24 ± 1.77	86.14 ± 3.09	0.00 *	80.00%
		3:00 PM	18	84.09 ± 2.91	92.13 ± 6.52	0.00 *	75.00%	75.40 ± 0.94	83.13 ± 5.17	0.00 *	58.33%
		4:00 PM	19	83.78 ± 3.51	94.46 ± 7.78	0.00 *	87.50%	74.96 ± 1.39	84.77 ± 3.58	0.00 *	75.00%
		5:00 PM	19	83.30 ± 2.11	89.76 ± 4.14	0.00 *	43.75%	74.71 ± 1.29	81.76 ± 3.43	0.00 *	56.25%
		6:00 PM	20	81.30 ± 3.63	84.47 ± 3.67	0.04 *	38.46%	74.37 ± 1.78	76.14 ± 2.41	0.04 *	7.69%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 10. Comparison of Secondary School Environmental Data to Meteorological Stations on Maui

Location	Distance to MS (miles)	On-Site Data Recommended	Rating of Recommendation	WBGT Equation
Kahului Airport (OGG)				
Baldwin High School	3.76	Yes	Moderately Recommended	WBGTmodified
Kamehameha Schools, Maui	7.90	Yes	Strongly Recommended	WBGT
Maui High School	2.94	Yes	Strongly Recommended	WBGTmodified
Kapalua Airport (JHM)				
Lahainaluna High School	3.96	Yes	Strongly Recommended	WBGT

MS=Meteorological station, WBGT=Wet bulb globe temperature index, WBGTmodified=Modified wet bulb globe temperature index

Table 11. Secondary School and Lihue Airport Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Kapa‘a High School											
	May	3:00 PM	6	82.33 ± 3.72	84.62 ± 5.15	0.06	16.67%	73.88 ± 2.26	76.27 ± 1.90	0.08	0.00%
		4:00 PM	8	81.25 ± 3.41	82.24 ± 4.56	0.63	0.00%	73.61 ± 2.31	74.39 ± 2.61	0.54	0.00%
		5:00 PM	12	79.25 ± 3.33	80.35 ± 5.14	0.54	16.67%	72.50 ± 2.40	74.26 ± 3.76	0.19	8.33%
		6:00 PM	9	76.67 ± 2.65	78.90 ± 5.70	0.30	44.44%	71.33 ± 2.54	72.66 ± 3.65	0.39	0.00%
		7:00 PM	6	76.17 ± 2.23	79.62 ± 5.50	0.19	66.67%	70.83 ± 2.99	72.63 ± 3.87	0.39	0.00%
	July	4:00 PM	4	88.00 ± 1.83	89.90 ± 3.96	0.42	25.00%	77.10 ± 1.07	81.28 ± 4.23	0.10	50.00%
		5:00 PM	6	85.50 ± 5.50	91.48 ± 4.88	0.07	66.67%	76.55 ± 2.26	81.22 ± 2.96	0.01 *	66.67%
		6:00 PM	6	83.50 ± 2.88	88.93 ± 4.90	0.04 *	66.67%	75.67 ± 1.20	79.02 ± 1.26	0.00 *	33.33%
		7:00 PM	5	81.40 ± 2.19	85.24 ± 5.52	0.19	20.00%	74.88 ± 1.44	76.10 ± 2.50	0.37	20.00%
	August	3:00 PM	14	89.57 ± 2.87	92.16 ± 3.49	0.04 *	50.00%	78.01 ± 1.21	80.11 ± 1.76	0.00 *	7.14%
		4:00 PM	21	88.05 ± 3.01	90.51 ± 3.66	0.02 *	33.33%	77.44 ± 1.32	79.32 ± 1.37	0.00 *	0.00%
		5:00 PM	22	85.77 ± 2.88	89.56 ± 2.73	0.00 *	27.27%	76.67 ± 1.16	81.20 ± 3.43	0.00 *	31.82%
		6:00 PM	24	83.71 ± 2.88	86.55 ± 3.10	0.00 *	22.73%	75.93 ± 1.24	78.73 ± 2.39	0.00 *	13.64%
		7:00 PM	15	81.47 ± 2.88	85.03 ± 2.65	0.00 *	40.00%	75.59 ± 1.26	76.69 ± 1.21	0.02 *	6.67%
	September	3:00 PM	12	89.17 ± 1.90	89.80 ± 4.77	0.67	58.33%	77.58 ± 1.10	79.45 ± 3.10	0.06	16.67%
		4:00 PM	15	87.89 ± 2.68	88.78 ± 3.05	0.41	40.00%	77.29 ± 1.39	79.45 ± 2.92	0.02 *	13.33%
		5:00 PM	15	85.67 ± 2.21	87.05 ± 3.45	0.20	26.67%	76.47 ± 1.20	78.90 ± 2.52	0.00 *	13.33%
		6:00 PM	11	83.55 ± 2.24	84.93 ± 1.80	0.13	0.00%	75.57 ± 1.43	76.61 ± 1.12	0.07	0.00%
		7:00 PM	6	83.06 ± 2.56	83.23 ± 1.47	0.89	16.67%	75.70 ± 1.33	75.52 ± 0.90	0.79	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 12. Secondary School and Kekaha Barking Sands Pacific Missile Range Facility Environmental Data

Secondary school	Month	Hour	Days of data per hour (N)	HI-MS Mean ± SD	HI-SS Mean ± SD	HI P-value	HI flag category difference	WBGT-MS Mean ± SD	WBGT-SS Mean ± SD	WBGT P-value	WBGT flag category difference
Waimea High School											
	May	3:00 PM	8	85.00 ± 1.69	86.04 ± 3.67	0.06	12.50%	74.91 ± 1.67	82.15 ± 2.14	0.00 *	62.50%
		4:00 PM	9	84.56 ± 2.30	84.57 ± 5.78	1.00	22.22%	74.92 ± 1.82	80.49 ± 2.94	0.00 *	22.22%
		5:00 PM	11	83.27 ± 2.41	79.21 ± 10.07	0.21	45.45%	74.54 ± 1.52	78.01 ± 3.26	0.00 *	18.18%
		6:00 PM	11	82.82 ± 2.48	78.41 ± 7.12	0.07	54.55%	74.12 ± 1.87	74.47 ± 2.20	0.69	0.00%
		7:00 PM	7	80.86 ± 2.91	75.34 ± 5.70	0.04 *	42.86%	73.09 ± 2.69	72.17 ± 2.04	0.49	0.00%
	July	4:00 PM	5	91.40 ± 1.82	94.14 ± 4.34	0.23	40.00%	78.54 ± 1.18	83.00 ± 2.37	0.01 *	60.00%
		5:00 PM	6	91.50 ± 2.59	91.80 ± 3.37	0.87	16.67%	78.63 ± 1.57	82.82 ± 3.79	0.03 *	66.67%
		6:00 PM	7	89.43 ± 3.36	89.14 ± 2.55	0.86	14.29%	77.70 ± 1.79	79.99 ± 2.86	0.10	28.57%
		7:00 PM	8	88.13 ± 2.42	85.13 ± 2.84	0.04 *	16.67%	77.24 ± 1.37	75.29 ± 2.08	0.04 *	0.00%
	August	3:00 PM	10	92.10 ± 2.73	96.35 ± 9.95	0.21	20.00%	78.86 ± 1.22	86.23 ± 4.42	0.00 *	80.00%
		4:00 PM	14	91.86 ± 1.99	92.12 ± 3.05	0.79	28.57%	78.80 ± 1.07	83.21 ± 3.50	0.00 *	57.14%
		5:00 PM	14	90.57 ± 1.22	90.81 ± 3.81	0.82	35.71%	78.34 ± 0.64	81.20 ± 2.95	0.00 *	42.86%
		6:00 PM	13	89.92 ± 1.66	91.82 ± 4.83	0.19	46.15%	78.18 ± 1.04	80.85 ± 2.47	0.00 *	38.46%
		7:00 PM	13	88.69 ± 1.03	87.13 ± 2.82	0.07	23.08%	77.61 ± 0.66	76.58 ± 1.38	0.02 *	0.00%

MS=Meteorological Station, SS=Secondary School, HI=Heat index, WBGT=Wet bulb globe temperature index, SD=Standard deviation, %=Percentage
*=Significantly different than MS

Table 13. Comparison of Secondary School Environmental Data to Meteorological Stations on Kaua‘i

Location	Distance to MS (miles)	On-Site Data Recommended	Rating of Recommendation	WBGT Equation
Lihue Airport (LIH)				
Kapa‘a High School	7.98	Yes	Moderately Recommended	WBGTmodified
Kekaha Barking Sands Pacific Missile Range Facility Airport (BKH)				
Waimea High School	9.04	Yes	Moderately Recommended	WBGTmodified

MS=Meteorological station, WBGTmodified=Modified wet bulb globe temperature index

Table 14. Meteorological Station Flag Category Underestimation

Measurement	Total Days of Flag Difference	Total^{+} (days)	Total^{+} (%)	1 Flag^{+} (days)	1 Flag^{+} (%)	2 Flags^{+} (days)	2 Flags^{+} (%)	3 Flags^{+} (days)	3 Flags^{+} (%)	4 Flags^{+} (days)	4 Flags^{+} (%)
HI	981	639	65.1%	612	62.4%	26	2.7%	1	0.1%	0	0.0%
WBGT	932	924	99.1%	695	74.6%	188	20.2%	32	3.4%	9	1.0%

HI=Heat Index, WBGT=Wet bulb globe temperature index, %=Percentage
+=Meteorological station flag category underestimation compared to secondary school flag category

DISCUSSION

Differences between on-site and meteorological station data at multiple secondary schools across the state of Hawai‘i suggest that on-site data collection is vital in determining appropriate activity modifications. Additionally, among schools where on-site data collection was recommended, $WBGT_{modified}$ equation was sufficient in most, but not all cases, for determining the appropriate WBGT flag category without the need for WBGT data which require T_{gt} to be collected. Furthermore, regardless of which WBGT equation was used, HI and WBGT flag categories were commonly underestimated by meteorological stations compared to on-site data, further supporting the recommendation to use on-site data to determine activity modifications at secondary schools in Hawai‘i.

Although the distance from a meteorological station to a secondary school may not seem significant enough to present with different environments, topography and surrounding buildings may create microclimates that affect each environment differently. Harlan et. al[14] presented the idea of Urban Heat Islands in which daytime heat was trapped with slower release of heat into the environment at night. Urban Heat Islands exist within cities where there are concentrations of heat-absorbing building materials compared to rural areas where soil, vegetation and open space aid in the release of heat. [14] However, due to the variability in topography and weather patterns in Hawai‘i, the results of the current study do not all align with the theory presented by Harlan et al. There is no clear data pattern presented among the secondary schools based on their location. For example, some secondary schools in urban areas had significantly different WBGT and HI values than their associated meteorological stations while other schools also in urban areas, had similar values to the regional station. Location-specific variations increase the need for collection of on-

site environmental data, therefore, to determine appropriate activity modifications, on-site data is recommended for locations with high variability in topography, weather patterns and surface types.

Underestimations of flag categories are of major concern when meteorological station data is used to determine activity modification recommendations for athletic activity. Although most differences were within one flag category of the on-site recommendations, this misrepresentation could put athletes, especially those who are susceptible to heat illness, at risk. For example, if at the same day and time a Red flag category, which only recommends an increase of water breaks, was assigned based on meteorological station data, though on-site data would have assigned a Black flag category, which recommends a cessation of practice, certain individuals may be at significant risk for the development of heat illness if only meteorological station data were available. Furthermore, no consensus on recommendations for activity modifications based on HI has been reached. The NOAA HI chart followed by most ATs provides categories of "Likelihood of heat disorders with prolonged exposure or strenuous activities", labeling a HI value as Caution, Extreme Caution, Danger and Extreme Danger.[20] However, no specific recommendations for activity modification are given for the categories using the NOAA HI chart. The Ohio State High School Association[21] provides guidelines for activity modification based on HI, but, these suggestions have not been validated, do not match the categories of the NOAA HI chart and lack applicability to other states. To provide the recommendations for athletic participation in extreme environmental conditions, guidelines given based on WBGT are most appropriate if WBGT is calculated from on-site data.

Calculating WBGT using the $WBGT_{modified}$ equation was shown to have little effect on the determination of activity modifications for many but not all secondary schools recommended for on-site data collection in the current study. For eleven secondary schools, T_{db} and T_{wb}

measurements were sufficient in identifying appropriate flag categories for the secondary school. This suggests that T_{db} and T_{wb} measurements may be obtained on-site-using devices such as a sling psychrometer[6] and applied to the $WBGT_{modified}$ equation to determine WBGT. This WBGT would result in the same flag category assignment as using on-site T_{db}, T_{wb} and T_{gt} applied to the WBGT equation. Should these secondary schools make changes to their environments, such as a change in surface types or surrounding construction, this recommendation may no longer be appropriate.

A known limitation in this study was related to the appropriate and consistent use of the Kestrel meter was by the AT at each secondary school to properly set up to record on-site data. Written instructions and troubleshooting guidelines were given to each school's AT at the beginning of the study in attempt to decrease operator error. Each AT was given the opportunity for in-person tutorials on set-up and data collection of the device and every effort was made to obtain the most accurate data, however, it was understood that the consistency of the set up at each secondary school could have varied and technological errors could have occurred. Additionally, the surface where the on-site data were measured or the consistency of hours per day that data were collected could have affected the evaluation of the secondary school's environment. Despite these limitations, the use of on-site environmental measurements to determine activity modifications was still recommended due to the overall amount of variability between sources of environmental data across time points analyzed.

The presence of microclimates in Hawai‘i caused differences in environmental data based on the method and location of evaluation which can affect an AT's clinical decision about activity modifications. Relying on inaccurate environmental data may be detrimental to an athlete's health while participating in strenuous activity, especially when environmental data is underestimated. Although a single secondary school was able to rely on NOAA data based on this study, most of

the secondary schools in Hawai‘i that were evaluated were not able to rely on NOAA data due to the effect microclimates have on determining local environmental conditions. These results are based on secondary school and meteorological station data in Hawai‘i, however, ATs at secondary schools in locations with variability in topography and weather patterns are also recommended to use on-site environmental data and the NATA activity modification suggestions to determine safe outdoor athletic activity participation.

LITERATURE REVIEW

Evaluating the thermal environment is important to determine appropriate parameters for safe athletic participation.[1] Since little can be done to change the environmental factors such as air movement, high humidity and temperature, behaviors must be adjusted in order to decrease overall heat stress to a tolerable level[4], including activity modifications. Recommendations for activity modifications and hydration protocols are provided by organizations such as the National Athletic Trainers' Association (NATA)[2] and the National Oceanic and Atmospheric Administration (NOAA)[5]. The wet bulb globe temperature index (WBGT) and heat index (HI) are two data points that can be used to evaluate the environment. Methods to evaluate WBGT and HI that are used include WBGT measurement device, such as a Kestrel 5400 Heat Stress Tracker, meteorological data collected at nearby stations and data collected on-site using a sling psychrometer. Each method of evaluation has benefits and limitations that affect the accuracy of the evaluation of the environment.

Heat Stress and Exercise

The human body has the ability to easily expend metabolic heat into the environment through radiation and convection from the skin in light work or cool environments.[1] As environments increase in heat or work becomes harder, bodies rely on the evaporative effect of the skin to cool.[1,2] However, there are factors in the environment that can limit that effect such as lack of air movement, high humidity and the amount of clothing restricting the skin on the body.[1] This limitation, if restricted by environmental conditions, can cause the body temperature to rise, cardiovascular system to strain, dehydration to occur and other regulatory malfunctions, causing the body to reach its heat tolerance.[1] If the body reaches this limit, symptoms such as dizziness and dehydration may occur, exposing the body to the possibility of heat illnesses such as heat exhaustion and heat stroke.[1]

Heat stress is considered to be a mix of behavior, physics and physiology, which can be analyzed to predict environmental conditions that the body would not be able to control its temperature in.[4] Behaviors such as rate of run or choice of clothing are underlying factors to heat stress in activity due to the vigorous exercise that causes stress to the thermoregulatory system.[4,22] Behaviors may also include the reactions that occur due to the body reaching its tolerance. Those behaviors may include seeking wind, loosening or removing clothing, or seeking shade.[1] The body's thermoregulatory system's job is to maintain a core body temperature of approximately 98.6° F (37°C).[2] The thermal environment can compound the thermoregulatory system and little can be done to change that environment.[4] The athlete must adjust their behavior to adjust their overall heat stress to a tolerable level.[4] To maintain a tolerable level of heat stress, six factors should be considered: metabolic heat production, thermal radiation, air temperature/humidity, air movement and clothing.[4,23,24] Metabolic heat load from muscular heat production must be balanced with an equal transfer of heat from the body to the external environment.[4] Physiological responses that are taken into consideration when discussing exercise heat stress are skin temperature, sweat rate and body core temperature.[4]

The purpose of evaluating heat stress that occurs due to the thermal environment is to determine the perceived risk of heat casualties during physical exertion under these conditions.[4] The NATA[2] currently supports recommendations for activity and rest-break guidelines that include limitations to activity in WBGT conditions greater than 92.1.[2] However, Brotherhood[4] states that the guidelines produced to prevent heat stress by recommending limits of sport participation do not provide justification or evidence for the limits. The recommendations are generally produced based on air temperature and relative humidity, more commonly the HI.[4] Brotherhood[4] expresses that the HI and WBGT are uninformative and are only useful when related to human responses.[4]

The history and limitations of the WBGT will be discussed further later. It was also stated "no index of heat stress, of itself, can reliably predict incidence of heat casualties"[4] due to the fact that heat stress includes individual factors such as heat production and transfer.

History and Limitations of WBGT

The WBGT was created in the 1950's to aid in controlling outbreaks of serious heat illnesses in the training camps of the United States military.[1] The WBGT not only considered the components of HI, dry bulb (T_{db}) and wet bulb (T_{wb}) measurements, but also considered black globe temperature measurements, which is solar radiation and wind speeds. The equation[1,2,7,10,11,13,15,25,26] for WBGT in outdoor conditions is:

$$WBGT = (T_{wb} \times 0.7) + (T_{gt} \times 0.2) + (T_{db} \times 0.1)$$

where T_{wb} was wet bulb temperature, T_{gt} was globe temperature and T_{db} was dry bulb temperature in degrees Fahrenheit.

When a means of measuring T_{gt} is not available, such as when indoors or when a T_{gt} is not available, the following modified equation[15,27,28] is used to calculate WBGT:

$$WBGT_{modified} = (T_{wb} \times 0.7) + (T_{db} \times 0.3)$$

where T_{wb} was wet bulb temperature and T_{db} was dry bulb temperature in degrees Fahrenheit.

These are important external environmental measurements to consider when determining heat stress. In this review, Budd[1] also explained the limitations of the WBGT. The largest limitation when using the WBGT is that it does not account for sweat evaporation variations.[4,6-11] For example, the type and amount of clothing that is being worn may cause variation in evaporation abilities, changing the amount of heat that is contained within the body. Another limitation of using WBGT measurement devices is that they may be expensive, difficult to calibrate and potentially erroneous if not used correctly. The potential for these errors have led many to

recommend to solely use measurements of air temperature and humidity and omit references to solar radiation or wind.[1] In addition, D'Ambrosio et al[7] states that WBGT measurement devices are not as easy to use as it has been marketed as. At times, WBGT values are being mistakenly interpreted as actual temperature values and then applied to the WBGT activity modification charts.[7] This causes misinterpretation and underestimation of the conditions that are present and the modification for activity needed. Finally, a downfall of using WBGT measurement devices to determine heat categories is that predictions for future temperatures cannot be made, whereas if meteorological station data are used, predictions and forecasts can be made.

Budd[1] states, "There is no single heat limit that can be applied to all situations". Varying microclimates should be taken into consideration when determining WBGT values.[2,6,8,10,15,22,25,29,30] Microclimates are local climates that differ in temperature, humidity, solar radiation and wind speeds to the larger surrounding climate.[12] These differences are caused by the varying amounts of heat or water trapped near the surface in that area.[12] Some changes that may occur include an increase in heat energy, a decrease in water causing a drier environment, or an increase in wind, removing heat and water vapor from the area, creating a cooler environment.[12] Harlan et al.[14] concluded that the level of heat exposure is correlated to location-specific measurements, for example, the amount of open space, regardless of the larger climate. This further supports the claim that estimates of local temperature and a person's exposure to excessive heat is highly dependent on the specific location of the measurements and that temperatures and humidity from a single central weather station of a city may over or under estimate conditions of the local climate. Harlan et al. [1415,16]

Grundstein et al[9] attempted to address this factor of microclimates by creating a regional heat safety threshold map for the contiguous United States. Local acclimatization and factors are

generally not accounted for in the WBGT, but this study took these into consideration. Activity modifications may be affected by geographic variations of heat exposure and acclimatization. Grundstein et al[9] proposed the following heat safety regions: Category 1 is WBGT readings less than 30° C, Category 2 is WBGT readings between 30.1-32.2° C and Category 3 is WBGT readings greater than 32.2° C. However, data were collected from airport observation stations for simplicity and consistent measures and not from on-site measurements. The variation between on-site WBGT verses airport observation station WBGT values was listed as a limitation, but not a focus, of this study. Grundstein et al[9] explained that the typical HI does not take into account the places that may have cooler or warmer climates than the general country's temperature. For example, the categories created in this study show lower values in cooler areas of Categories 1 and 2 than the HI suggests.

WBGT v. HI

The WBGT and HI are commonly mistaken for the same values. Although they are both methods of environmental evaluation, HI only considers T_{wb} and T_{db} temperatures. As previously mentioned, WBGT considers those values in addition to solar radiation and wind speed.[1,2,5,7,10,11,13,15,25,29] The National Oceanic and Atmospheric Administration's National Weather Service (NWS) outlines the differences in factors between WBGT and HI.[5] To determine HI, relative humidity and air temperature values are applied to a temperature-humidity/HI chart developed by R.G. Steadman in 1979[31], readily accessible on the websites such as the NWS website.[5]

WBGT Measurement Devices v. Meteorological Station Data

There have been several studies that compare the use of WBGT measurement devices to meteorological data collected at automated stations.[8-10,13,15,25] Cheuvront et al[13] compared the WBGT values collected at three different sites along the path of the Boston Marathon using a

Kestrel meter for WBGT measurements on-site, from the Schneider Electric online database and from meteorological stations nearby. The values were then used to determine WBGT categories to determine activity restrictions/modifications. On-site WBGT values collected using the Kestrel were compared to the meteorological stations WBGT values as well as the predicted values from Schneider Electric to determine the accuracy of each method. Cheuvront et al[13] discovered that HI categories were significantly underestimated as much as one category level when using meteorological station data or predicted Schneider Electric data in comparison to on-site Kestrel data. Research conducted by D'Ambrosio et al[32] suggests that although it is possible to gain a general evaluation of the thermal environment indirectly through air temperature, mean radiant temperature, humidity and air velocity measurements, inaccurate T_{wb} values may also be obtained.[32] The WBGT is considered user friendly, frequently used and can be beneficial if used correctly and appropriately in conditions that may be different from the ones the devices were designed in.[32]

In contrast, studies conducted by Grimmer et al[8], D'Ambrosio et al[7], Patel et al[15], Moran et al[11] and Maia et al[10], have shown that using the ambient temperature, relative humidity, solar radiation and wind velocity data collected from meteorological stations may be sufficient enough to give an idea of the environment and how activity should be modified.[7,8,10,11,15] This data can be used to calculate a value similar to that calculated by the WBGT measurement devices, using equations such as the Lilijgren model[25], the Matthew model, the Hunter and Minyard model and the WBGT equation.[8,10,11,15] Although these models have been tested, further research needs to be conducted to validate them in various environmental conditions.[10,15,28] Researchers have attempted to create equations that can determine WBGT without the use of a WBGT measurement device, such as a Kestrel. These equations consider variables from the use of a sling psychrometer

or from data archived by the National Oceanic and Atmospheric Administration's National Climactic Data Center (NCDC) and published daily by the NWS.[28] The NWS provides an abundant amount of information about the environment but since radiant heat is still not recorded by the NWS, the equations created to predict WBGT from NWS meteorological data are not valid. Lemke et al[28] suggested obtaining radiant heat from the National Aeronautics and Space Administration online database. However, the data published is not hourly and not immediately or readily available. Although the equations suggested by previous researchers may be sufficient enough to use, they are not valid in determining WBGT.[28]

Previous research has suggested that the use of HI values produced by the NOAA or values obtained using ambient temperature and relative humidity values on a HI chart, may be sufficient enough to produce protection of heat to those participating in thermal environments.[5,29,33] Dimiceli et al[26] introduced a formula that is currently being tested to estimate black globe temperatures using data readily available to the public, published by the NWS.[26] The NWS currently has the algorithm in use for limited areas in Oklahoma through a website that allows input of ambient temperature and an approximation of the average wind speed to calculate local WBGT.[26] The goal is to be able to apply this data nationally and add WBGT it to the list of values that the NWS currently provides.[26]

There are two main benefits to using meteorological station data: 1) there is little to no cost to obtaining these values verses the cost of a WBGT measurement device[7,10,15,25] and 2) weather and environmental condition forecasts can be predicted using forecasted data.[13,15,25] However, a major limitation of using data from meteorological stations include the possibility of having significant differences or underestimations of weather severity due to the generalization of the data for the area in which the meteorological stations are collection data for.[8-10,13]

WBGT v. Other Methods of Comparison

Budd[6] proposed the use of a sling psychrometer and air velocity and radiant heat measures determined by personal opinion as a method to determine a general idea of the environmental condition for potential activity modification. Two limitations to this method include the purchasing of a sling psychrometer and the potential under/overestimations of thermal stress. Moran et al[11] developed a stress index that included other factors that the WBGT does not called the Environmental Stress Index (ESI). The ESI was shown to be comparable to the WBGT, providing another option of measuring the condition of the environment and thermal stress without the hassle of a WBGT measurement device or sling psychrometer. In contrast, Brotherhood stated that heat stress indices that record values above 100% differ from WBGT values.[4] A study conducted by Lee et al[3] compared WBGT to the Hong Kong Heat Index (HKHI). To create the HKHI, researchers used local heat stress data and hospitalization data to determine the optimal T_{wb}, T_{db} and T_{gt} coefficients for Hong Kong. Lee et al discovered that the HKHI was more accurate at reflecting environments of increased heat stress in Hong Kong, suggesting that the applicability of WBGT may vary based on location due to acclimatization, environment, activity and population.[3]

MacPherson[34] created a chronological review of indices of thermal stress, categorizing each index into indices based on measurement of physical factors, indices based on physiological strain and indices based on the calculation of heat exchange.[34] Physical factor indices included T_{db} and T_{wb}; thermo-integrator index which is a measurement of combined influences of air temperature and movement and radiation upon human comfort; wind chill index: a measurement of cooling power of atmosphere, wind velocity and air temperature; equivalent temperature using a Eupatheoscope, "measure of combined effect of temperature, speed of air and temperature of surroundings"; Katathermometer for determining atmospheric conditions that are healthy and

comfortable; and globe-thermometer temperature: a combined effect of air temp, air movement, mean radiant temp on thermal comfort.[30] Indices based on physiological strain include the effective temperature index-T_{db} and T_{wb} plotted on a psychrometric chart to determine line of comfort; intersection of comfort line with dew point; corrected effective temperature-globe thermometer substituted for dry temperature; equivalent effective temperature corrected for radiation which is the use globe temperature instead of dry with given dew point and given air movement; the equatorial comfort index: degree of comfort in terms of environmental factors of temperature, humidity and air speed; the index of physiological effect: effect of exposure to heat on heart rate, skin temperature, rectal temperature and sweat loss plotted on a psychrometric chart; the predicted four-hour sweat rate for determining rectal temperature, amount of sweat, temperature, humidity, movement of air, temperature of surroundings, clothing worn and energy expenditures; the index for evaluating heat stress: the rate of energy expenditure, radiation exchange and surrounding temperature; thermal strain index: heat transfer mechanisms and observations of body reactions; and the WBGT which is the effect of sun and terrain radiation, air temp, humidity, wind speed.[30] Indices that are considered under the category of calculations of heat exchange include the thermal acceptance ratio-heat acceptance of environment of an unclothed person, rate of heat production of the body, vapor pressure of the air, air temperature and temperature of the surroundings-; operative temperature index-measurement of net physical effect of surrounding walls and ambient temperature; and standard operative temperature index: measurement of wall and air temperature, air movement and skin temperature.[30]

The perceptual strain index (PeSI) was developed by Chan et al[35] as an alternative method of evaluating heat strain. The PeSI was found to be sensitive to WBGT variants and is simpler to use.[35] This method provides little to no risk of equipment or user error to measure heat strain.[35]

Chan et al considers this method easy to understand and an acceptable measurement of approximations of physiological strain, providing guidelines for monitoring that strain.[35] However, this index has not been validated in outdoor or uncontrolled conditions.[35]

The universal thermal climate index (UTCI) is another index of thermal stress that has been critiqued.[23,36,37] The UTCI accounts for human thermoregulation based on clothing adjustments, impact of air temperature, air humidity, air velocity and thermal radiation, to predict stress parameters on the body.[23] Brocherie et al[36] emphasized the usefulness of the UTCI as it being a "promising index to assess athlete physiological responses to humidity". Kampmann et al[23] compared the UTCI to the predicted heat strain index (PHS; measurement of rectal temperature, sweat rate, and duration of limited exposures) and WBGT.[23] Predicted heat strain index and UTCI values for predicted sweat rate were shown to be similar, whereas UTCI overestimated high relative humidity when compared to the PHS.[23] For rectal temperature, the PHS underestimated predicted values and the WBGT overestimated those values.[23] Overall, the Kampmann suggests that the UTCI, PHS and WBGT can give relatively similar estimations and may be interchangeably used.[23] However, it should also be noted that the UTCI does not consider inter-individual variability which are differences in individual metabolic rates, and is not a comprehensive representation of actual sporting events.[36,37]

Activity Modification Recommendations

The WBGT and HI values can be applied to a type of activity modification chart[2] to determine restrictions for activity or to a heat category chart[38] to determine the severity of the heat. The NATA provides Activity/Rest Break Guidelines in their Heat Illness Position Statement.[2] This chart outlines the WBGT readings and respective recommendations for activity modifications to prevent heat illnesses in hot and humid environmental conditions.[2] The U.S. Army Training and Doctrine Command[38] published a Guide to Risk Management of Heat Casualties, which

contained a Work/Rest/Water Consumption Guide. This guide provides work to rest or continuous work and water intake recommendations for Easy, Moderate and Hard work as well as heat categories for WBGT readings. Patel et al [15] also provided current heat categories and guidelines for continuous work while in warm weather conditions. Modifications are made based on the values evaluated in the environment that the activity is taking place, reinforcing the need to determine accurate WBGT and HI values.

There are varying opinions and research behind the best and most accurate method of evaluation of the environment. Each method is dependent on the resources and data available. Although the access to use and upkeep of a WBGT measurement device may be feasible for some to evaluate the immediate environment, using meteorological data from online databases or HI values may be sufficient to evaluate the environment and ensure proper activity modifications can be made.[7,8,10,11,15,22] Therefore, the purpose of this study is two-fold: 1) to compare environmental data obtained by an on-site heat stress monitor at secondary schools in Hawai‘i to regional meteorological station data from the NOAA and 2) to compare activity modification recommendations based on the collected WBGT and HI values from both locations.

APPENDIX A: SECONDARY SCHOOLS AND ASSOCIATED METEOROLOGICAL STATIONS

Island	MS	Secondary School	Secondary School Zip Code	Distance to MS (miles)
O‘ahu	Honolulu International Airport (HNL)	‘Aiea High School	96701	4.2
		Kula Kaiapuni 'O Ānuenue	96816	8.8
		Damien Memorial School	96817	3.7
		Farrington High School	96817	3.4
		‘Iolani School	96826	7.2
		Kaimukī High School	96816	7.6
		Kaiser High School	96825	15.0
		Kalani High School	96821	10.3
		McKinley High School	96814	5.4
		Mid Pacific	96822	7.2
		Moanalua High School	96818	2.0
		Saint Louis School	96816	8.1
	Kalaeloa Airport (JRF)	Campbell High School	96706	4.0
	Kāne‘ohe Marine Corps Air Station (KMCAS)	Castle High School	96744	3.6
		Kailua High School	96734	3.1
	Wheeler Air Force Base (WAFB)	Wai‘anae High School	96792	10.9
Island of Hawai'i	Kona International Airport at Keāhole (KOA)	Konawaena High School	96750	17.9
Maui	Kahului Airport (OGG)	Baldwin High School	96793	3.8
		Kamehameha Schools, Maui	96768	7.9
		Maui High School	96732	2.9
	Kapalua Airport (JHM)	Lahainaluna High School	96761	4.0
Kaua‘i	Lihue Airport (LIH)	Kapa‘a High School	96746	8.0
	Kekaha Barking Sands Pacific Missile Range Facility Airport (BKH)	Waimea High School	96796	9.0

MS=Meteorological Station

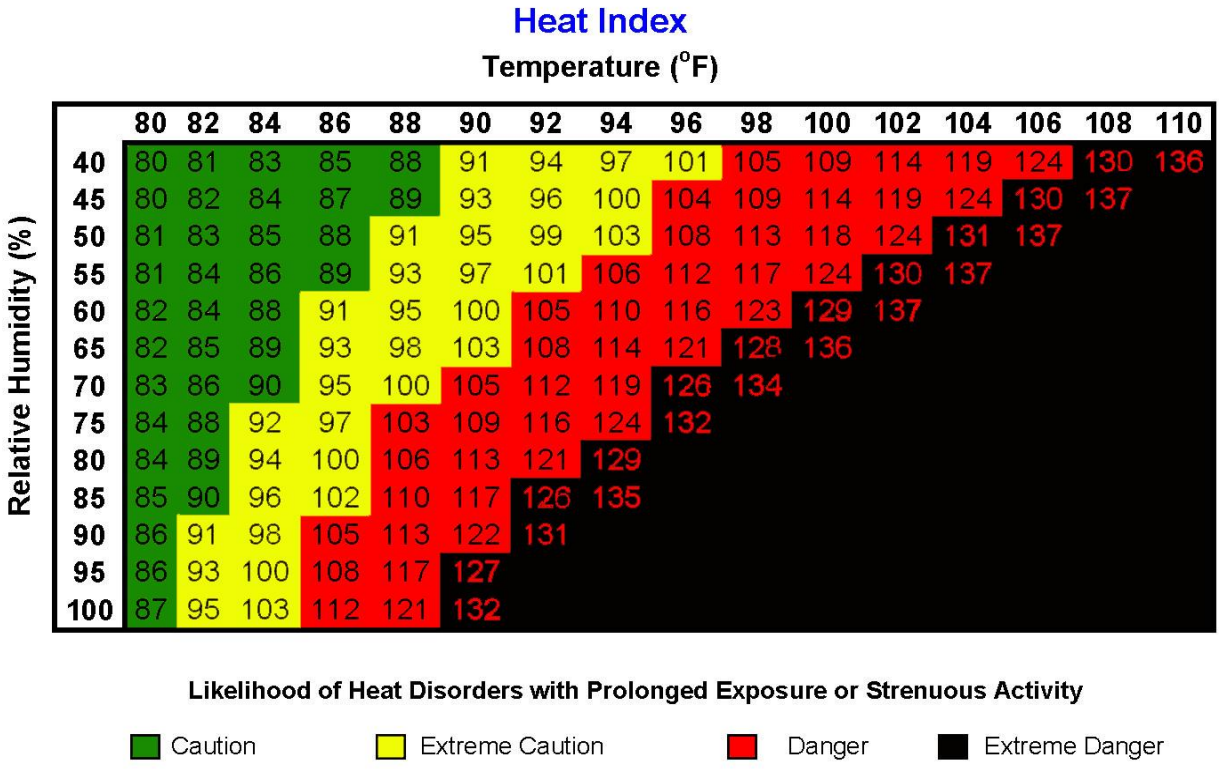
APPENDIX B: GEORGIA HIGH SCHOOL ATHLETIC ASSOCIATION WBGT

ACTIVITY/REST BREAK GUIDELINES

Category	WBGT (°F)	Activity/Rest Break Guidelines
None	Under 82.0	Normal activities. Provide 3 separate rest breaks (minimum 3 minutes each) per hour during workout.
Green	82.0-86.9	Use discretion for intense or prolonged exercise. Watch at-risk players carefully. Provide 3 separate rest breaks (minimum 4 minutes each) per hour during workout.
Yellow	87.0-89.9	Maximum practice time=2 hours For football: players restricted to helmet, shoulder pads, and shorts during practice. All protective equipment must be removed for conditioning activities. For all sports: provide 4 separate rest breaks (minimum duration 4 minutes each) per hour during workout.
Red	90.0-92.0	Maximum length of practice=1 hour No protective equipment may be worn during practice and there may be no conditioning activities. There must be 20 minutes of rest breaks provided during the hour of practice.
Black	>92.1	No outdoor workouts, cancel exercise, delay practices until a cooler WBGT reading occurs.

WBGT=Wet bulb globe temperature index, °F=degrees Fahrenheit, >=Greater than

APPENDIX C: HI CHART



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